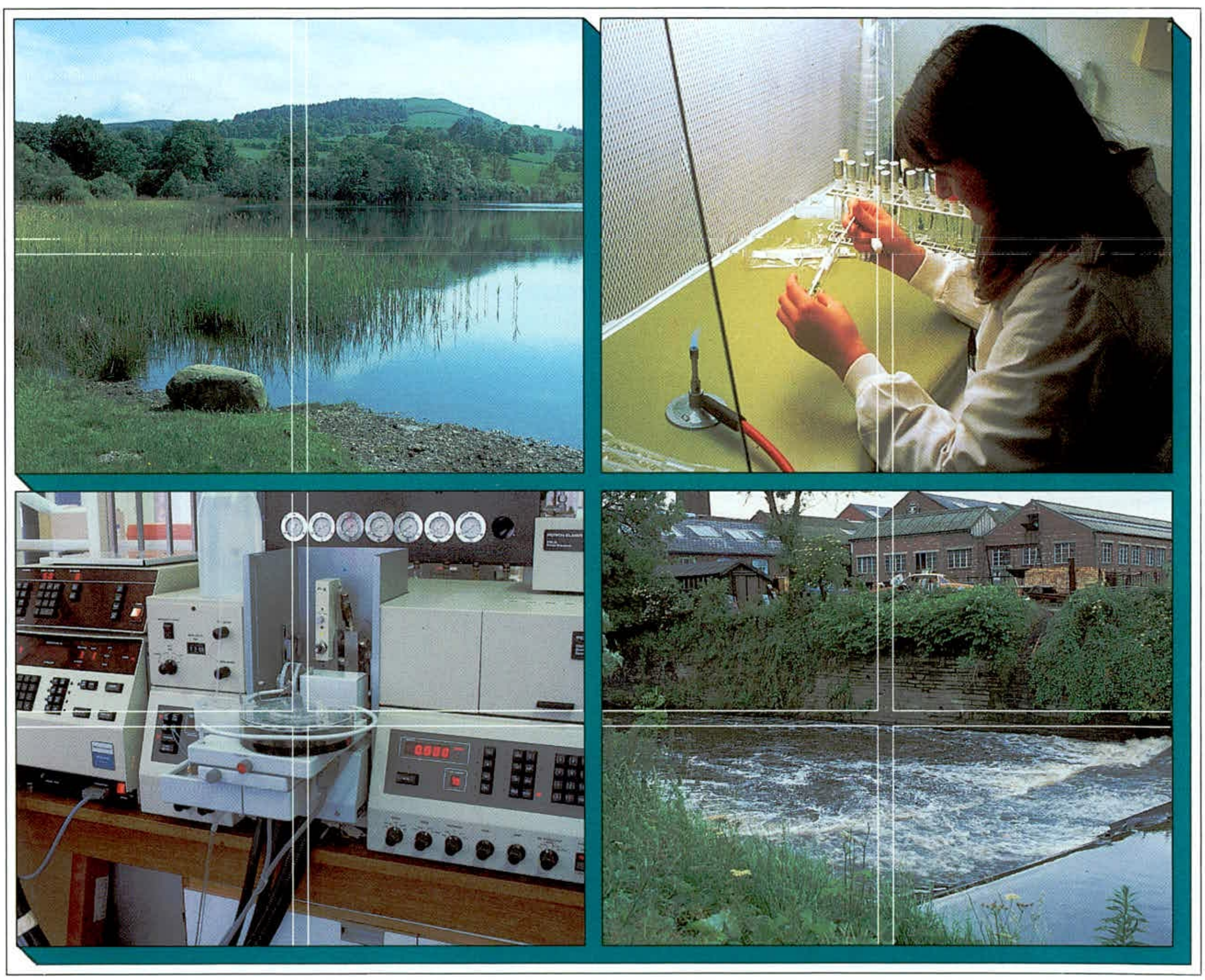
Institute of Freshwater Ecology

THERMAL STABILITY AND WATER QUALITY OF THE PROPOSED KARAMEH DAM RESERVOIR, KINGDOM OF JORDAN

J Hilton

Report To: Gibb Environmental
TFS Project No: T04050u1
IFE Report Ref.No: RL/T04050u1/1



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Contract Start Date:	1992
Report Date:	May 1992
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Thermal stability and water quality of the proposed Karameh dam Reservoir, Kingdom of Jordan.

Report to Gibb Environmental.
May 1992.

By J.Hilton.

This report makes its recommendations from a state of the art understanding of the way in which aquatic systems work and is considered to represent the best advice available at the present time. However it should be borne in mind that changes in the physical and chemical properties of water are driven by a complex interaction of biological, chemical and physical processes which are still not entirely predictable and the Institute cannot guarantee that changes will occur exactly as predicted.

The Institute of Freshwater Ecology is part of the Terrestrial and Freshwater Sciences Directorate of the Natural Environment Research Council.

Executive summary.

The reservoir is likely to show monomictic behaviour with the thermocline approaching to within 6m of the surface in mid-summer. Stratification will begin in May and end in the latter half of October.

It is unlikely that salt release from the bottom will combine with thermal density gradients to create conditions of continuous stratification but arrangements must be made to monitor temperature and salinity profiles for the first few years of service and to make provision for release of the total contents of the hypolimnion if necessary.

About 40% of the incoming boron may be trapped in the sediments of the reservoir, so that concentrations in the water column will probably stabilise at about half the flow weighted mean concentration of the inflows.

Calculations suggest that the reservoir will be able to maintain very high algal populations which will significantly reduce water quality in the hypolimnion. Light will probably be limiting so that very large blue-green algal populations will develop in the surface waters during calm periods. High algal toxin levels could be generated in these circumstances. Draw off levels will be subjected to inundation by very high concentrations of wind blow algal scums many times during a year.

Extensions of intake levels 1 and 2 further from the shore are recommended. Because of the light limitation, destratification would be a very effective management tool to improve water quality.

Contents.

1. Introduction.

1.1 In order to increase the development of irrigation at the southern end of the Jordan valley, an earth fill embankment dam is proposed. The dam would create a storage reservoir in the Wadi Mallaha, which is a tributary of the Jordan river. The Karameh reservoir will be filled in the winter by transferring water by pipeline from the King Abdullah canal. In summer it will be returned to the canal for use downstream.

1.2 The IFE study, commenced in October 1991. This report gives predictions of the likely stratification behaviour of the reservoir and the likely water quality for selected water quality parameters, mainly nutrients.

1.3 Basic data for the the reservoir are given in table 1.1

Table 1.1 Physical, chemical and hydrological properties of the Karameh reservoir.

Location	32° 13'N, 35° 37'E
Catchment Area[1] (p.2)	61.2 Km^2
Lake surface area[2]	4.0 km^2
Maximum length[2]	4.6 km
Maximum width[2]	1.6 km
Maximum volume[3]	$55x10^6$ m^3
Mean depth (Max vol/Max area)	13.75 m
Maximum depth[4]	33 m
Mean annual inflow data[5]	
Catchment- Wadi Mallaha	
hydraulic contribution	150 l/s
mean phosphorus concentration	1.2 mg/l
mean nitrate concentration	159 mg/l
King Abdullah Canal	
hydraulic contribution	750 l/s
mean phosphorus concentration	1.81 mg/l
mean nitrate concentration	30.85 mg/l
Flow weighted total	
hydraulic contribution	900 l/s
mean phosphorus concentration	1.71 mg/l
mean nitrate concentration	52.21 mg/l

Table 2.1 continued.

Mean annual inflow data - 50% base flow diversion.[5]

Catchment- Wadi Mallaha	
hydraulic contribution	75 l/s
mean phosphorus concentration	1.2 mg/l
mean nitrate concentration	159 mg/l
King Abdullah Canal	
hydraulic contribution	750 l/s
mean phosphorus concentration	1.81 mg/l
mean nitrate concentration	30.85 mg/l
Flow weighted total	
hydraulic contribution	825 l/s
mean phosphorus concentration	1.75 mg/l
mean nitrate concentration	42.50 mg/l

1. Storage facilities in the Wadi Mallaha Karameh Dam Project. Sir Alexander Gibb and Partners (SAG & P). Interim report Feb. 1992.
2. Estimated from a diagram supplied by SAG & P. (Project layout).
3. Schedule 1 of the tender document.
4. From a bathometric map supplied by SAG & P.
5. supplied by SAG & P.

2. Stratification.

2.1 Standing water bodies receive heat from the sun at different rates throughout the day and throughout the year. They are also exposed to winds of different speeds and directions which vary over similar time scales as the heat input. The incoming heat will warm some or all of the water. The warmer water will expand and become less dense. As a result the warmer, less dense water will tend to float on top of the cooler, more dense bottom water, and so isolate the bottom water from further heat inputs. The wind, on the other hand, transfers kinetic energy to the water, creating turbulent movements which try to disperse the heat throughout the whole water body. Hence the thermal structure of a water body results from a complex balancing of the ability of the kinetic energy of the wind to overcome the buoyancy provided by the net heat input. The likelihood of stratification occurring in a reservoir can be inferred from estimates of the Monin-Obukov length (Spigel, Imberger and Rayner, 1986) and the Wedderburn number (Imberger and Hamblin, 1982). The former predicting the relative stability of the buoyancy effects compared to the wind energy, and the latter predicting the depth of mixing for a given density difference.

2.2 At a latitude of 32°N the solar flux is about 22 MJ m^{-2} d^{-1} in January rising to about 43 MJ m^{-2} d^{-1} in July/ August. About two thirds of this, at most, reaches the ground due to absorption and scatter by the atmosphere. By rearranging the Monin-Obukov equation it is possible to estimate the minimum wind speed required to fully mix the lake for a given heat input. The maximum and minimum wind speeds required to achieve this mixing are given in table 2.1 for days near the winter minimum, the summer maximum and the equinoxal heat input rates. These calculations assume that prior to each date no stratification has taken place and, in the absence of other data, that the water temperature equals the mean air temperature for the previous two months. Because of the thermal capacity of the water in the reservoir the water temperature will lag behind the air temperature so that use of this assumption will slightly underestimate the water temperature in January and slightly overestimate the temperature in July. This will tend to reduce the stability in winter while making little difference to the stability in summer.

2.3 In winter, the mean wind speed is just less than the lower end of the range of minimum wind speeds required to completely mix the reservoir. Given that occasional very high wind speeds are experienced and that the actual stability is likely to be reduced due to the underestimate of the water temperature in January, it is likely that the reservoir will not stratify during the winter. This is corroborated by calculations of the Wedderburn number which suggest that the temperature of the surface water would need to reach 29 °C, from its starting temperature of 15 °C, in order to remain stratified under the average high wind speeds.

2.4 In the summer the estimated minimum wind speeds required to fully mix the system increase slightly. However, the cloud cover will decrease so that the actual minimum wind speed will approach the upper of the two figures. In addition the observed mean wind speed reduces significantly (Meteorological Department, 1988) , and the maximum speed of occasional gusts reduces significantly. All these factors combine to suggest that the reservoir will stratify in the summer. This is corroborated by a rearrangement of the Wedderburn equation which suggests that the surface water would only need to develop a temperature differential of a few degrees to achieve stratification.

2.5 The calculations suggest that the reservoir will be monomictic (stratify once a year, during the summer). The annual wind patterns (Meteorological Department, 1988) show that average wind speeds reduce considerably in May/ June from an average of about 3.5 Kn to 2.9 Kn. In addition maximum wind speeds reduce from about 40 Kn to around 30 Kn at the same time so that stratification is likely to set in some time in May. Between October and November there is a rapid increase in mean wind speed from about 3 Kn to over 4 Kn. Maximum wind speeds show a step increase between September and October. Hence, stratification is likely to break down towards the end of October (the occasional high wind speeds in september will be acting against strong stratification so that they are less likely to be effective than later in the year when temperatures will have dropped.

2.6 Assuming a temperature of about 24°C in mid May (ie the temperature of the bottom water) and a surface temperature of about 29°C then the thermocline is likely to reach a maximum average depth of about 6m below the surface at full capacity. Experience suggests that this will result in a mean thermocline depth of about 10 m. However, significant changes in thermocline depth are likely to occur on a 24 hr cycle due to diurnal fluctuations in temperature. On calm days a secondary thermocline will develop very close to the surface, within about the top metre.

2.7 The previous analysis assumes that density differences are only due to temperature differences. High concentrations of dissolved salts can also raise the density of water. They could result from either submerged saline inflows or through the leaching of salt from the flooded soils (Gibb environmental, 1987). A report argued that submerged saline inflows were unlikely to occur. However the local soils contain high concentrations of salt. It has been calculated that, in the first 25 years of the reservoir's life, 1350 tonnes of salt could be leached from each hectare of soil. On an average yearly basis this is equivalent to 5.4 tonnes per hectare per year (although release will take place at a much greater rate in the early years, probably at least 20 tonnes /ha/y, and at a much slower rate later on).

2.8 From the ratio between the Monin-Obukov length and the Eckman depth it is possible to estimate the vertical mixing time. Values of the order of 30 minutes result for total mixing of the reservoir in the winter. This rate is sufficiently fast that density gradients are unlikely to develop near the sediment and create a salinity stratification.

2.9 However, during the summer, when stratification occurs, the leached salt will be trapped in the hypolimnion. Assuming a conical shape with a maximum depth of 33m, a radius of 1262m (equivalent to a lake of total volume 55×10^6 m^3 and surface area 5×10^6 m^2) and a mean thermocline depth of 10m, the salt concentration in the bottom water should not rise by more than 7 mg/l. This is unlikely to create a significant change in the density gradient. Hence, the creation of meromictic conditions (continuous stratification) by the combination of saline and thermal stratification is unlikely. However, it would be prudent to make a provision for monitoring the temperature and salinity gradient across the thermocline in the first few years of service and to allow for the possibility of releasing the total contents of the hypolimnion at the end of the summer during the first few (say 3) years of service if meromixis does occur.

Table 2.1. Assumed water temperatures, estimated wind speeds required to mix the incoming heat throughout the water column at different times of the year in the proposed Wadi Mallaha Reservoir and mean and maximum wind speeds from data tables (Met Dept., 1988)

	Jan 31	Apr 1	July 31	Sept 31
Water temp. °C	15.2	20.0	31.0	28.2
Wind speed (Kn) Min cloud cover	7.5	8.3	8.9	8.8
Wind speed (Kn) Max cloud cover	5.1	5.6	6.0	5.9
mean wind speed (Kn)	4.0	3.5	2.8	2.9
max wind speed (Kn)	49	43	28	33

3. Boron chemistry.

3.1 The range of crops grown in irrigated areas using saline waters is often limited by boron (B) concentrations. However, very little is known about its chemistry in fresh waters. At concentrations below 0.025M (270 mg/l as B) it is normally present either as undissociated boric acid or as the borate ion (Waggott, 1969).

$$B(OH)_3 + H_2O \rightleftharpoons B(OH)_4^- + H^+$$

This equilibrium is pH dependent (Choi and Chen, 1979). About 44% of any borate present will be associated with either Ca, Mg or Na (Eisler, 1990). Since the pK of boric acid is 9.2 significant dissociation of $B(OH)_3$ will not occur at pH below 9.2.

3.2 Boron is not removed in normal sewage treatment processes (Wagott, 1969) and it is not easily precipitated under normal environmental conditions (Carriker and Brezonik, 1978). Hence its concentration in water is controlled by its sorption properties (Wedepohl, 1978). At this point controversy reigns. In laboratory experiments there is general agreement that B is absorbed by activated charcoal (>90% removal - Choi and Chen, 1979); and by illite (Wedepohl, 1978), which tends to sorb B irreversibly. However, Carriker and Brezonik (1978) showed that B was not sorbed by kaolinite or attapulgite. Wedepohl (1978) reported similar results for kaolinite but found that adsorption to bentonite depends on the presence of Na, Ca and Mg, particularly the latter. However, Fanning and Maynard (1978), among others, reported no uptake of B by particulate material in estuarine situations and Carriker and Brezonik (1978) found that B concentrations in Florida rivers only appeared to reduce by dilution.

3.3 This controversy is clarified a little by Blume at al. (1978) who showed that solids can adsorb or desorb B depending on the pH. At a pH of about 8, which is the pH of water at the proposed dam site (Gibb, 1992), adsorption will probably predominate. However, the adsorption is weak (K_d approx. 1) so that the main loss process will probably be uptake by algae, followed by deposition. In the Tegeler Lake, in Germany, about 40% of the total incoming boron was trapped in the sediment, much of it in a hot water soluble form, which usually indicates uptake by cellular material. Hence, concentrations in the lake were about half the incoming concentration. By extrapolation we might expect the boron concentration in the Wadi Mallaha to stabilise at about 5mg/l if the water comes mainly from the local surroundings and <0.1 mg/l if the majority of the water derives from the King Abdullah canal. Obviously mixtures of the two sources will result in an intermediate level.

4. Effects of algal growth on water quality.

4.1 The growth of algae in water is influenced by many things. Research carried out over many years has established that, for temperate lakes, reasonably reliable estimates of the size of algal crops can be made by considering five main factors: the amount/ concentration of available nutrients; the relative balance between different nutrients; the residence time in the lake; the light environment; the wind patterns. In this report several equations will be used to estimate algal biomass in the Karameh reservoir. These equations were originally developed for northern temperate lakes. However, in spite of observed differences between temperate and tropical/ sub-tropical lakes and reservoirs, present evidence supports the belief that control of eutrophication in the tropics can be considered in essentially the same manner as in temperate zones (Ryding and Rast, 1989). In the absence of other means the normal predictive equations will be used, but it is likely that algal crops will be slightly higher than those predicted by equations based on the effects of nutrient limitation.

4.2 Physical and chemical data used for the estimation of likely water quality in the present and enlarged reservoir are given in table 1.1. Estimates of P and N loadings and concentrations are given in table 4.2. Chlorophyll a concentrations have been estimated for different depths of completely mixed surface water when either different nutrients or light are assumed to limit growth.

4.3 The mean concentrations of phosphorus and nitrogen (nitrate) in the reservoir are estimated at 2.6 and 79 mg/l respectively. On the basis of either of these two nutrient concentrations the reservoir would be considered as hyper-eutrophic (OECD, 1982)

4.4 There are a large number of empirical equations which can be used to predict chlorophyll concentrations from either total (or soluble reactive) phosphorus or total nitrogen (or nitrate) concentrations (Ryding and Rast, 1989). They all make different assumptions and predict different descriptors of algal biomass. The following discussion will use four measures which have been widely used in predictive situations. Vollenweider's equation (OECD, 1982) has been used to predict the mean annual chlorophyll a concentration which could be attained for a given P loading. Dillon and Rigler's equation (1974) can be used to estimate the mean summer chlorophyll a levels assuming P limitation and Sakomoto's equation (1966) gives the equivalent assuming N limitation. Reynolds' equation is a predictor of maximum summer chlorophyll a (Reynolds, 1991). Reynolds has also given the equations for calculating the maximum algal biomass sustainable for a given light intensity (Reynolds, 1991).

4.5 With a mean hydraulic residence time of 2 years, there is plenty of time for algal biomass to develop to its full potential. The average standing crop of algae in the reservoir could reach over 200 µg/l chlorophyll a when the reservoir is stratified to its mean expected thermocline depth of 10m and the epilimnion is well mixed down to this depth. Maximum biomass concentrations could reach at least 630 µg/l. At these biomass levels P concentrations would be reduced to near zero and N concentrations would reduce to about 60 mg/l as N. Denitrification would probably reduce this to below 30mg/l.

4.6 The mean phosphorus loading is so large that the Dillon and Rigler equation for mean summer chlorophyll estimation appears to be unreliable. It is included for comparison with the Sakamoto estimate which assumes nitrogen limitation. Both equations produce very high estimates of biomass but the P limited value is much lower than the N limited concentration. Hence, the phosphorus is likely to be the growth limiting nutrient and nitrogen fixing blue greens are unlikely to have an ecological advantage.

4.7 A comparison of the estimates of biomass concentrations which can be sustained under light limitation and under P limitation is given in table 4.2. Under all assumptions of limitation for a given mixed depth, the biomass estimates are about the same. Although the differences are small, in fact, slightly higher biomasses are achieved if P limitation is assumed. As a result, light will be the growth limiting factor. This has a major benefit and a major disadvantage.

4.8 The disadvantage is that, under these circumstances efficient light utilisers or light interceptors will dominate. Because of their ability to float near to the surface and capture light, there is a high possibility that blue green algae will dominate, particularly under the very calm wind conditions which persist for much of the summer. Chlorophyll concentrations of over a 1000 µg/l in the top metre or so of the reservoir could be common. This has no effect if the water is to be used purely for irrigation, particularly as the water could be drawn off below the algal rich level. However, several blue green algal species can produce toxic substances and, at these high algal concentrations the toxin concentrations could become toxic to livestock and humans if the water were also used for livestock (or serendipitous human) consumption. With the high salinity, species such as prymnesium could also develop, producing fish toxins which can devastate fish populations.

4.9 On the positive side, Because light is limiting, the algal population can be controlled by mixing. If the reservoir were to be artificially destratified, then chlorophyll concentrations would be unlikely to exceed an annual mean of about 60 µg/l. Because of the turbulence created by the mixing, the weak buoyancy developed by blue green algal would not produce a strong enough upward force to allow the development of surface scums. Hence, by one management operation, the mean biomass would be reduced and dominance by potentially toxin producing blue green algae would be removed.

4.10 High concentration algal scums created during the frequent calm periods in summer would then be prone to collection at the down wind end of the reservoir when light breezes occured after a calm period. 42% of the time (over a ten year average) is calm. Of the 58% of the remaining time, 23% blows from the north and 13% from the W and NW. Since the draw off tower is down wind of these directions all three take off points are within the sphere of influence of wind blown algae. draw off three wil be unaffected by this effect, if it is usable because of deoxygenation of the hypolimnion see 4.10, but take off point 1, and possibly 2 could be jepardised. Provision of extensions to take off points 1 and 2 to about the same point as take off 3 would protect the water quality from degradation by north and NW winds. Destratification would elimiate this problem completely, but draw off extensions should still be considered if destratification equipment could be out of use for significant periods of time, compared to the requirement for irrigation water.

4.11 Because of the high algal productivity which is expected to occur in the Karameh reservoir it is very likely that the hypolimnion will rapidly deoxygenate very soon after stratification. This will result in a major deterioration in water abstracted from the hypolimnion, ie below about 10 m, on average. The water will have no oxygen and have high concentrations (tens, possibly hundreds of mg/l) of ammonia, iron, manganese and sulphide. This will reduce it's acceptability for irrigation purposes but, probably more importantly, it will create a major oxygen demand on the King Abdullah canal if it is returned to it during the period of stratification. In their own right they will also constitute a significant quantity of substances toxic to both aquatic biological species and to man and animals.

4.12 The land which is being flooded is desert scrub land, hence there will be no significant, extra nutrient input during the first few years of operation due to decaying vegetation.

4.13 Complete flushing of the reservoir at a frequency of about once every eight years when the electrical conductivity reaches 8000 µS/cm (SAG &P, pers comm) will have no significant effect on the algal predictions since it occurs at a much lower frequency than the flushing rate.

4.14 As far as nutrients are concerned the Karameh reservoir will be phosphorus limited. The King Abdullah canal has a significantly higher P mean concentration than the base flow. Diversion of 50% of the base flow will only increase the weighted mean inflow concentration by 2%. The phosphorus loading will only reduce by 6% so that the estimated nutrient limited production will only be marginally smaller than estimates with no diversion.

4.15 Algal productivity is therefore unlikely to change, over the 1, 5, 10 or 15 year timescale, from the levels predicted for the, so called, base case (no diversion or flushing) irrespective of the hypothesised diversion or flushing alternatives.

Table 4.1 Calculated nutrient and chlorophyll concentrations assuming different limitations to growth.

	Nitrogen	Phosphorus	
hydraulic displacement time	1.94 years		
areal loading ($g/m^2/a$)	370	12.1	
in-lake concentration (mg/l)	79	2.6	
Chlorophyll a concs under nutrient limitation			
mean annual (µg/l)[1]		145	mixed
mean annual (µg/l)[1]		212	stratify
mean summer (µg/l)	27,000[2]	6500[3]	
max summer (µg/l)[4]		630	

Chlorophyll a (µg/l) assuming

	summer solstice light limitation	equinox light limitation	OECD[1] Phosphorus limitation
Fully mixed	63	50	145
mean stratified depth (9m)	105	86	211
mixed layer = 1m	1115	940	1580
mixed layer = 3m	358	300	580

1. OECD, 1982
2. Sakamoto, 1966
3. Dillon and Rigler, 1974
4. Reynolds, 1991

5.Conclusions.

5.1 The reservoir will stratify in summer (May to October) and mix fully in winter.

5.2 The mean thermocline depth will be about 10 m below the surface. The upper limit of the thermocline will be about 6 m. However, on calm days a second thermocline will develop within a metre or so of the surface.

5.3 Salt release from the soil is unlikely to instigate permanent stratification.

5.4 Boron concentrations in the reservoir are likely to be about half the lvels estimated by simple inorganic mixing models.

5.5 The stratified reservoir could maintain mean annual algal concentrations of at least 200 µg/l.

5.6 Phosphorus is likely to be the limiting nutrient.

5.7 Blue-green algae are unlikely to have sufficient ecological advantage that they will dominate algal populations.

5.8 Light will probably be the growth limiting factor, so that, in conjunction with significant periods of no wind, buoyant, blue-green algae will develop large surface blooms (up to 1000 µg/l.

5.9 High blue-green algal concentrations could result in the production of high toxin concentrations in the water.

5.10 Large blue green algal surface scums are likely to form wind blown mats around the intakes during a significant number of occasions during the year.

5.11 High algal concentrations in the reservoir will result in rapid dexoygenation of the hypolimnion and the formation of high concentrations of polluting substances therein.

5.12 Because light is limiting, continuous mixing of the reservoir will significantly improve water quality.

5.13 Complete flushing of the system every 8 years or so will have no effect on algal biomass.

5.14 Diversion of 50% of the catchment inflow will have little effect on the algae in the reservoir.

5.15 Diversion and flushing are unlikely to have any effect on algal growth over 1, 5, 10 or 15 year periods.

6. Recommendations.

6.1 In the first few years of operation temperature and salinity profiles should be taken at about monthly intervals to check that salt release is not faster than expected and that permanent stratification is not developing.

6.2 Provision should be made to release the hypolimnetic water if permanent stratification occurs in the firts few years of operation.

6.3 Destratification should be given consideration as an effective means of maintaining water quality.

6.4 Consideration should be given to extending draw offs 1 and 2 to the same distance from the shore as number 3 so as to avoid the worst effects of wind blown algae.

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